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Farm-Level Effects of Adopting Herbicide-Tolerant Soybeans in the U.S.A.

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ABSTRACT

This paper estimates the on-farm impacts of adopting herbicide-tolerant soybean on herbicide use, yields, and farm profits, using an econometric model that corrects for self-selection and simultaneity and is consistent with profit maximization. The model is estimated using nationwide farm-level survey data for 1997. Given that the use of herbicide-tolerant soybeans involves the substitution of a particular herbicide—primarily glyphosate—for other herbicides, we explicitly consider this substitution process in the model.

Key Words: *Genetically engineered soybeans, herbicide tolerance, herbicide use, farm profits, technology adoption, yields.*

The development of agricultural chemicals and new crop varieties offering enhanced yields and pest resistance has contributed to unprecedented agricultural productivity growth in the U.S. during the past century. These seed and chemical technologies have been widely adopted by farmers, allowing them to increase yields and reduce production costs. However, the potential hazard of chemical pesticides to human health and the environment have caused increased concern. Modern biotechnology techniques, such as genetic engineering,[1] can increase the efficiency and precision of introducing improved traits into important crop varieties and often have been embraced as a potential means for maintaining agricultural productivity while decreasing the use of harmful chemicals.

The first generation of genetically engineered (GE) crops commercialized are those with enhanced pest management traits, such as herbicide tolerance and insect resistance. Herbicide-tolerant crops contain genes that allow them to survive certain herbicides that previously would have destroyed the crop along with the targeted weeds.[2] This allows farmers

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[1] Genetic engineering (genetic modification of organisms by recombinant DNA techniques) is used to develop crops containing genes that impart a crop with the ability to express desirable traits, allowing the targeting of single plant traits and facilitating the development of characteristics not possible through traditional plant breeding techniques.

[2] The most common herbicide-tolerant crops are Roundup Ready® crops resistant to glyphosate, an herbicide effective on many species of grasses, broadleaf weeds, and sedges. Glyphosate tolerance has been incorporated into soybeans, corn, canola, and cotton. Other genetically modified herbicide-tolerant crops include corn resistant to glufosinate-ammonium, and cotton resistant to bromoxynil. There are also traditionally

to use more effective postemergent herbicides, expanding weed management options (Carpenter and Gianessi).[3] Adoption has risen dramatically in only a few years since commercial availability, particularly for herbicide-tolerant soybeans. Herbicide-tolerant soybean varieties, for example, became available to farmers in limited quantities in 1996. Its usage quickly expanded to about 17 percent of soybean acreage in 1997 to more than 60 percent of the soybean acreage in 2000 (USDA, 1999a, b, 2000).

A major element in assessing the farm-level impacts of GE crops is their microeconomic impact. Faced with reduced returns to crop production caused by low commodity prices, farmers examine biotechnology as a potential means for reducing costs and/or increasing yields, thereby improving financial performance. Rapid adoption of herbicide-tolerant soybean varieties by U.S. farmers suggests that the perceived benefits of these technologies have outweighed the expected costs. Herbicide-tolerant soybeans provide a broad spectrum of potential benefits and appeal to farmers because they promise to simplify and increase the effectiveness of pest management, reduce its costs, and increase flexibility in field operations.[3]

However, estimation of the benefits and costs associated with the adoption of herbicide-tolerant soybeans is complicated because those benefits and costs vary by region, depending on soils, weather, weed infestations, the development of popular regional crop varieties containing these genes to ensure yield advantages, seed costs, and technology fees. Moreover, it is difficult to isolate the impact of GE crops because the impact is often confounded with the effect of other production practices (such as conservation tillage, crop rotation, other pest-management practices), and management ability.

The health and environmental impacts stemming from changes in pesticide use associated with adoption are surely another important element in assessing the effects of GE crop adoption (Royal Society, Henry A. Wallace Center). A poll of farmers and consumers in August 1999 indicated that 73 percent of consumers were willing to accept biotechnology as a means of reducing chemical pesticides used in food production. Also, 68 percent said that farm chemicals entering ground and surface water was a major problem (Farm Bureau/Philip Morris Gap Research). And more recently, a survey of consumer attitudes suggested that 70 percent of consumers would be likely to buy a variety of produce "if it had been modified by biotechnology to be protected from insect damage and required fewer pesticide applications." (IFIC Foundation).

Although farmers using herbicide-tolerant crops continue to use chemical herbicides, the herbicides that are used, particularly glyphosate, often require a smaller number of applications and are more benign than many of the traditional herbicides (Roberts, Pendergrass, and Hayes; Culpepper and York; Marra, Carlson, and Hubbell). Therefore, proponents claim that the use of herbicide-tolerant crops may benefit the environment by reducing the use of potentially harmful synthetic herbicides that could be transported into waterways or lead to residue in/on food. However, some scientists and many consumer and environmental groups are not convinced that the use of these crops would decrease herbicide use and argue that herbicide-tolerant crops could foster farmers' reliance on herbicides.[4]

Many field-test and enterprise studies have examined the yield and cost effects of using genetically engineered crops.[5] In the case of

bred herbicide-tolerant crops, such as soybeans resistant to sulfonylurea.

[3] For example, herbicide-tolerant crops may alleviate any problems arising from the carryover of herbicides. Farmers may be able to practice strip-cropping (a practice where corn and soybeans are grown in alternating rows). Also, farmers that use production practices such as notill may benefit if the adoption of herbicide-tolerant crops allows them to use a more effective herbicide treatment system.

[4] Another concern is that extensive use of these crops could lead to the development of weed resistance. Concerns have also been raised that herbicide-tolerant crops may pass their genes to weedy relatives, thereby making those weeds resistant to herbicides.

[5] For example, Arnold, Shaw, and Medlin; Culpepper and York; Delannay *et al.*; Ferrell, Witt, and Slack; Goldman *et al.*; Keeling *et al.*; Roberts, Pendergrass,

soybeans, except for the study by Delannay *et al.* who found no yield effects, the results indicated that the use of herbicide-tolerant soybeans had a positive effect on yields. Most of the studies based on experimental data also found greater net returns with the use of herbicide-tolerant soybeans, indicating that increased yields and savings in herbicide costs were enough to outweigh higher seed costs and the technology fee.[6] However, while findings based on experimental data have mostly shown that herbicide-tolerant crops compared favorably to conventional varieties, results from producer surveys have not been definitive. Research using data from 1997 and 1998 cost-of-production surveys in Mississippi suggested that pesticide costs were lower with Roundup Ready soybeans, but these lower pesticide costs did not cover the added technology fee (Couvillion). McBride and Brooks compared mean seed and pest-control costs estimated from a 1997 national survey of soybean producers. Results of the comparison did not show a cost advantage or disadvantage for herbicide-tolerant versus conventional soybean varieties.

While farm surveys have the potential to provide realistic results under farm conditions, many of the studies based on these type of data have been limited to comparing means of adopters and non adopters. However, a comparison of means may be misleading when using data from "uncontrolled experiments," as is the case with farm-survey data. Conditions other than the "treatment" are not equal in farm surveys. Thus differences between mean estimates for yields from survey results cannot necessarily be attributed to the adoption of GE crops since the results are influenced by many other factors not controlled for, including irrigation, weather, soils, nutrient and pest-management practices, other cropping practices, operator characteristics, pest pressures, etc. This limitation can be overcome using econometric methods that statistically control for factors considered relevant. That is, differences in economic conditions and crop, management practices, and operator characteristics are held constant so that the effect of adoption can be observed.

This paper presents the first econometric estimate of the farm-level effects of adopting herbicide-tolerant soybeans based on nationwide farm-level survey data. In particular, we estimate the effect of herbicide-tolerant soybeans on herbicide use, crop yields, and farm profits using an econometric model that corrects for self-selection and simultaneity. Given that the use of herbicide-tolerant soybeans involves the substitution of a particular herbicide—primarily glyphosate—for other herbicides, we explicitly consider this substitution process in the model.

Empirical Analysis

This section presents the empirical evaluation of the effect of adopting herbicide-tolerant soybeans on herbicide use, yields, and farm profits, using 1997 nationwide survey data. After briefly showing survey results on the reasons given by farmers for adopting these crops, we present the econometric model used to examine the impact of adoption.

Reasons for Adoption According to Farmers

The majority of farmers surveyed (65 percent of adopters) indicated that the main reason

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and Hayes; Vencill). However, few survey-based studies have been reported on the economic and chemical use effect of adopting these crops (Fernandez-Cornejo and Klotz-Ingram; Marra, Carlson, and Hubbell; McBride and Brooks, 2000).

[6] Data from field trials in West Tennessee were used in an economic analysis of Roundup Ready soybeans (Roberts, Pendergrass, and Hayes). Comparing per-acre net returns from 14 trials, the returns from the Roundup system were 13 percent higher than the returns for the second most profitable system. Higher returns from the Roundup system resulted from both higher yields and lower herbicide costs. Research results from experimental trials in Mississippi (Arnold, Shaw, and, Medlin) also showed higher yields and net returns from Roundup Ready soybeans versus conventional varieties. Other partial budgeting results also showed higher returns from Roundup Ready versus conventional weed control for soybeans (Marra, Carlson, and Hubbell; Reddy and Whiting). However, research using experimental data on Roundup Ready and conventional corn varieties in Kentucky did not show a significant difference in returns above seed, herbicide, and fixed costs (Ferrell, Witt, and Slack).

they adopted herbicide-tolerant soybeans was to "increase yields through improved pest control." The second top reason, stated by nearly 20 percent of adopters, was "to decrease pesticide costs." All other reasons combined amounted to about 15 percent of adopters. These results confirm other adoption studies pioneered by Griliches who showed that expected profitability positively influences the adoption of agricultural innovations. Hence, factors expected to increase profitability by increasing revenues per acre (price of the crop times yield) or reducing costs are generally expected to positively influence adoption. Given that an objective of pest management in agriculture is to reduce crop yield losses, there is a high incentive for innovations that reduce these losses.

The Theoretical Framework

The model takes into consideration that farmers' adoption and pesticide-use decisions may be simultaneous, due to unmeasured variables correlated with both adoption and pesticide demand, such as the size of the pest population, pest resistance, farm location, and grower perceptions about pest-control methods (Burrows). The model also corrects for self-selectivity to prevent biasing the results (Greene, 1997). Finally, the model ensures that the pesticide demand functions are consistent with farmers' optimization behavior, since the demand for pesticidal inputs is a derived demand.

To account for simultaneity and self-selectivity we use a two-stage model. The first stage consists of the *adoption decision model*—for the adoption of herbicide-tolerant crops as well as for other weed management practices that might affect herbicide use. The adoption decision model is estimated by probit analysis. The second stage is the *impact model* that provides estimates of the impact of using herbicide-tolerant crops on herbicide use, yields, and farm profits. To achieve consistency, the herbicide demand and supply functions are derived from a profit function and estimated together as a system with the profit function.

The Adoption Decision Model

The adoption of a new technology is essentially a choice between two alternatives, the traditional technology and the new one. Growers are assumed to make their decisions by choosing the alternative that maximizes their perceived utility (Fernandez-Cornejo, Beach, and Huang; Fernandez-Cornejo, 1996, 1998). Assuming that the disturbances are independently and identically normally distributed, their difference will also be normally distributed and the probit transformation can be used to model the adoption decision. Thus if F denotes the cumulative normal distribution, the probability of adoption of technology k is $P(I_k = 1) = F(\delta_k' Z_k)$ and the adoption equation is $I_k = \delta_k' Z_k + \mu_k$, where I_k denotes the adoption of a herbicide-tolerant crop ($k = 1$), and (to control for in the second stage) weed management techniques such as scouting ($k = 2$), other weed management practices like changing planting/harvesting dates, alternating herbicides, changing row spacing, and mowing ($k = 3$), and Z_k is the vector of explanatory variables.[7]

The factors or attributes influencing adoption included in the vector Z, with the rationale to include them in parentheses, are (i) farm size (other studies show that operators of larger farms are more likely to adopt innovations), (ii) farmer education (more educated farmers are often found to be more eager to adopt innovations), (iii) experience (older farmers are more reluctant to accept newer techniques), (iv) weed infestation levels/target pests (farmers expecting worse infestation levels are more likely to take advantage of glyphosate, thus adopting it), (v) crop price (operators expecting higher prices are also more likely to expect higher margins and are more likely to adopt agricultural innovations), (vi) seed price (higher prices reduce margins), (vii) use of conventional tillage (expected to negatively influence adoption, as those operations using conventional tillage have less need for herbicides

[7] As Burrows notes, it is convenient to interpret this equation as the probability, conditional on Z, that a particular grower will adopt.

Table 1. Sample Means and Definition of Main Variables—Soybean Producers, 1997

Variable	Description	Mean
Variable profits	Per-acre revenues minus per-acre variable costs, \$ per acre. Variable costs the farmers that adopt the herbicide-tolerant soybeans	251.3
Yield	Soybean yield measured in bushels per acre	39.92
Herbicide use Ingredients	Average number of applications, calculated by dividing the sum (over all ingredients active in the given herbicide family) of the treatment acres by the number of acres treated	‡
Size	Dummy variable = 1 if annual sales are greater than or equal to \$500,000	0.08
Education	Dummy variable = 1 if operator had some college or more	0.43
Experience	Operator experience. Actual number of years operating a farm	25.3
Infestation level 1, 2	Dummy variable = 1 if infestation levels for weeds Type 1 (mostly annual grasses like foxtail) or Type 2 (perennial grasses, broadleafs) were worse than normal	0.15/0.11
Seed cost	Actual cost of soybean seed, \$ per acre	16.86
Debt-to-assets ratio	Dummy variable = 1 if the actual ratio is greater or equal to 0.4	0.14
Contract	Percent of soybean revenues under contract	0.053
Conventional tillage	Dummy variable = 1 if farmer used conventional tillage	0.54
Crop price	Actual price of soybeans, \$ per bushel.	6.59
Price of herbicides	Weighted average price of active ingredients of a given herbicide family	‡
Rotation	Dummy variable = 1 if crops in the field were rotated in the last 3 years	0.56
Herbicide tolerant	Binary variable = 1 if herbicide-tolerant seeds were adopted in the field	0.11
Scouting	Binary variable = 1 if weed scouting was performed in the field	0.77
Other weed control	Binary variable = 1 if other weed control practices were adopted in the field	0.43

‡ Vector that includes several variables, one for each family.

compared to operators using conservation or no-till practices), (viii) contractual arrangements for the production/marketing of the crop (contracts often specify the acreage to be grown or quantity and quality of product to be delivered and may also require application of selected inputs), and (ix) the debt-to-asset ratio used as a proxy for risk (as risk-averse farmers are less likely to adopt agricultural innovations, Feder et al., 1985). Variable definitions and sample means are presented in Table 1.

The Impact Model

Unlike the traditional selectivity model in which the effects are calculated using the subsamples of adopters and nonadopters separately, the impact model uses all the observations and is known as a "treatment effects model," used by Barnow, Cain, and Goldberger). In this model the observed indicator variable, I, indicates the presence or absence of some treatment (e.g., use of herbicide-tolerant crops) (Greene, 1995).

Formally, given the unobserved or latent variable $I^* = \delta'Z + \mu$ and its observed counterpart I (such that $I = 1$ if $I^* > 0$ and $I = 0$ if $I^* \leq 0$), the treatment-effects equation which is the basis for our impact model is Y $\beta'X - \alpha I + \epsilon$.

Following Maddala (p. 260) and Greene (1995, p. 642, 643) we can obtain consistent estimates of β and α by regarding self-selection as a source of endogenity. Thus there are two sources for the endogeneity of the variable I, namely the simultaneity discussed earlier (farmers' adoption and herbicide use decisions are simultaneous) and self-selection. Because of this endogeneity (of I), we can not use the actual adoption values of I in the impact model. For this reason we use the predicted probabilities of adoption, obtained from the probit equations, as instrumental variables for I. As indicated in the previous section, in our adoption decision model we have three indicator variables and consequently three probits, as I_k, $k = 1, 2, 3$.

To examine the impact of using herbicide-tolerant soybeans on herbicide use, yields, and farm profits, we specify the herbicide demand functions, the supply function, and the variable profit function as a simultaneous system. To model explicitly the substitution of glyphosate by other herbicides we specify three herbicide demand functions considering three herbicide families (Table 2): (i) acetamides (acetochlor, alachlor, metolachlor, and propachlor), which are mainly applied as pre-emergence herbicides; (ii) glyphosate; and (iii) other synthetic herbicides, which include 2,4-D, acifluorfen, bentazon, metribuzin, imazethapyr, and pendimethalin, several of which are being replaced by glyphosate.

Using a normalized quadratic restricted profit function (Diewert and Ostensoe; Fernandez-Cornejo, 1996, 1998), considering land as a fixed input and a single output (soybean), imposing symmetry by sharing parameters and linear homogeneity by normalization; using the price of labor as numeraire and appending disturbance terms, the per-acre profit function ($\tilde{\pi}$), per-acre supply function ($\tilde{Y}$), and the three per-acre herbicide demand functions (vector with three components, $\tilde{X}_1$ for the acetamides, $\tilde{X}_2$ for glyphosate, and $\tilde{X}_3$ for other herbicides), become:

$$(1)\quad \tilde{\pi} = A_0 + A_y P + \sum_j A_j W_j + \sum_k C_k R_k + 0.5 G_{yy} P^2 + \sum_j G_{yj} P W_j + \sum_k F_{yk} P R_k + 0.5 \sum_j \sum_i G_{ij} W_i W_j + \sum_k \sum_j E_{jk} W_j R_k + 0.5 \sum_i C_{ik} R_i R_k + \epsilon_\pi$$

$$(2)\quad \tilde{Y} = A_y + G_{yy} P + \sum_j G_{yj} W_j + \sum_k F_{yk} R_k \epsilon$$

$$(3)\quad \tilde{X}_1 = A_1 + G_{y1} P + \sum_j G_{1j} W_j + \sum_k E_{1k} R_k + \epsilon_1$$

$$(4)\quad \tilde{X}_2 = A_2 + G_{y2} P + \sum_j G_{2j} W_j + \sum_k E_{2k} R_k + \epsilon_2$$

$$(5)\quad \tilde{X}_3 = A_3 + G_{y3} P + \sum_j G_{3j} W_j + \sum_k E_{3k} R_k + \epsilon_3$$

where P and W are the output and input prices—A, C, E, F, and G—are parameters. The vector of other factors $\boldsymbol{R}$ includes weed infestation levels (expected to negatively affect profits), rotation and tillage (cropping practices known to affect the use of herbicides).[8] The vector $\boldsymbol{R}$ also includes the predicted probabilities of adoption (obtained from the probit equations) of herbicide-tolerant soybeans as well as other weed-management practices that might affect the use of herbicides.

Data and Estimation

The model is estimated using data obtained from the nationwide Agricultural Resource Management Study (ARMS) consolidated surveys developed by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS) of USDA and conducted in 1997. The ARMS survey was designed to link the resources used in agricultural production to technologies and farm financial/economic conditions for selected field crops. In particular, ARMS survey data can be used to link the adoption of genetically

[8] Tillage choice (i.e. conventional vs. conservation tillage) was considered as an exogenous variable because of previous results: Soule and Klotz-Ingram, using the Wu-Hausman and 1997 data, tested the hypotheses that (i) the tillage use decision is exogenous to the adoption of herbicide-tolerant soybeans and (ii) that the adoption of herbicide-tolerant soybeans is exogenous to the tillage decision. While they rejected the hypothesis (ii), exogeneity of the adoption of herbicide tolerant soybeans in the tillage decision model, they *could not reject* hypothesis (i) exogeneity of the tillage variable in the model for adoption of herbicide-tolerant soybeans. These results are also consistent with the rather high degree of adoption of conservation tillage (more than 50 percent of the soybean acreage) in 1995, the year before herbicide tolerant soybeans were introduced into the market, given that tillage choice is usually long term (farmers that adopt period t are also likely to adopt period t+1).

Table 2. Major Herbicides Used on Soybeans, 1997[1]

Herbicide Active Ingredient	Area Applied	Applications	Rate per Crop Year	Total Applied
	Percent	Number[2]	Lbs/Acre	Million Lbs
Acetamides				
Metolachlor	7	1.1	1.87	8.91
Alachlor	3	1.0	2.36	4.50
				13.41
Glyphosate	28	1.3	0.81	14.92
Other herbicides				
Pendimethalin	25	1.1	1.06	17.53
Trifluralin	21	1.0	0.88	12.27
Bentazon	11	1.0	0.65	4.74
Clomazone	5	1.0	0.71	2.32
2, 4-D	8	1.0	0.39	2.11
Acifluorfen	12	1.0	0.21	1.69
Metribuzin	10	1.0	0.25	1.69
Imazethapyr	38	1.0	0.05	1.24
Sethoxydim	7	1.0	0.21	1.03
				49.88[3]
Total				78.21

[1] Planted acres: 66.2 million acres for the 19 states surveyed.
[2] Number of times a treated acre receives the particular active ingredient.
[3] Includes other herbicides not listed.
Source: USDA, 1998.

engineered crops with yields, other management techniques, chemical use, and profits.

The data were obtained using a three-phase process (screening, obtaining production practices and cost data, and obtaining financial information) (Kott and Fetter). The 1997 survey was conducted through on-site interviews based on a probability sample, drawn from a list frame based on all known commercial soybean growers of the states selected. The 1997 soybean survey covered 19 states, which account for 93 percent of the U.S. soybean production. The third phase included 17 states—Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Mississippi, Michigan, Minnesota, Missouri, Nebraska, North Carolina, Ohio, South Dakota, Tennessee, and Wisconsin. After excluding observations with missing values, 1444 observations from 17 states were available for analysis.

The survey included a section on pesticide use by active ingredient. In this study we grouped the herbicide active ingredients into three families. In addition to pesticide use, the survey included questions on yields, prices, cropping practices, and use of other inputs. The survey also included questions regarding the use of herbicide-tolerant varieties.

For the empirical evaluation, the three probit equations are estimated separately as there is no gain in estimation efficiency by using a seemingly unrelated regression (SUR) framework when the regressors are the same across all the equations and there are no theoretical restrictions for the regression coefficients (Dwivedi and Srivastava).[9] However,

[9] A bivariate probit model was considered in preliminary runs. These estimates showed that the correlation coefficient between the disturbances of the two probit equations was not significant, implying that the disturbances associated with the probit equations were not related and that separate probit equations could be used to obtain the predicted probabilities used in the second stage of the model. Given these results, considering that there are no efficient techniques to estimate a multinomial probit with more than two choices

Table 3. Estimates for Adoption, Per-acre Herbicide Demand, and Supply Equations—U.S. Soybean Producers, 1997

	Probit Estimates		
	Adoption of		
	Herbicide-tolerant	Weed Scouting	Other Weed Control
Variable	Parameter Estimates		
INTERCEPT	−7.752**	1.106	4.815
Size	0.444***	0.090	0.005
Education	0.314**	0.124*	0.172**
Experience	0.002	−0.005	0.000
Infestation level 1	0.571**	−0.192	0.193
Infestation level 2	−0.655**	−0.165	−0.160
Seed price	0.059***	−0.007	−0.002
Debt to assets ratio	−0.107	−0.078	−0.064
Contract	0.390	0.073**	0.076*
Conventional tillage	−0.221*	−0.145*	−0.091*
Crop Price	0.733*	−0.012	−0.705*
Price of acetamide herbicides			
Price of other herbicides			
Price of glyphosate herbicides			
Infestation level			
Rotation			
Conventional tillage			
Prob. adoption, herb. tolerant			
Prob. adoption, scouting			
Prob. adoption, other weed			

***, **, * Significant at the 1-percent, 5-percent and 10-percent level.

the equations for the second stage (equations 1–5) are estimated together to gain estimation efficiency. That is, the per-acre supply and three demand equations are estimated together with the per-acre profit function in an iterated seemingly unrelated regression (ITSUR) framework (Zellner).

The impact of adoption of herbicide-tolerant soybeans on herbicide use is calculated from equations (3)–(5). For example, from equation (4) the impact of using herbicide-tolerant soybean on glyphosate herbicide use is $\partial\tilde{X}_2/\partial R_4 = E_{24}$. The elasticity of glyphosate herbicide use with respect to the probability of adoption of herbicide-tolerant soybeans is $E_{24}(R_4/X_2)$. Similarly, the elasticity of "other herbicides" use with respect to the probability of adoption of herbicide-tolerant soybeans is $E_{34}(R_4/X_3)$.

Unlike Burrows, who used expenditures (because of lack of data) in the pesticide demand equation, this paper uses the number of herbicide applications per year, which is a better measure of pesticide use. The average number of applications per year is calculated by dividing the sum (over all active ingredients in the given herbicide family) of the treatment acres (number of acres treated by an herbicide active ingredient times the number of treatments of that herbicide during the year) by the number of acres treated (receiving one or more applications of the given herbicide active ingredient).[10] For comparison, we also use

(Greene, 1997) other than Dorfman's method based on Gibbs sampling and taking into account the econometric issues arising with the use of Dorfman's technique because of self-selection (Wu and Babcok), we discarded the use of multinomial probit.

[10] The average number of applications per year may be any positive number, not necessarily an integer.

Table 3. (Extended)

ITSUR Estimates							
Acetamides Demand		Glyphosate Demand		Other Herbicides Demand		Per-Acre Soybean Supply	
Parameter	t-Value Estimates	Parameter	t-Value Estimates	Parameter Estimates	t-Value	Parameter Estimates	t-Value
−0.061	−0.53	−0.213	−1.05	0.713	0.73	31.58***	3.27
−0.034	−1.14	−0.013	−0.33	0.736***	7.15	9.68***	2.67
0.700***	22.20	0.001	0.11	−0.003	−1.09	−0.034	−1.14
−0.003	−1.09	−0.005	−1.41	0.015	0.30	0.736***	7.15
0.001	0.11	0.373***	33.70	−0.005	−1.41	−0.013	−0.33
−0.003	−0.23	−0.013	0.83	−0.281**	−2.48	−2.453**	−2.91
−0.001	−0.07	−0.032	−1.61	0.184*	2.13	0.374	0.56
−0.031	−1.43	0.017	0.28	−0.264	−0.74	−4.970***	−3.78
0.051	−0.97	0.480***	3.50	−1.644***	−3.31	6.918**	2.26
0.264	1.27	0.121	0.46	1.654	1.19	0.677	0.13
−0.184	−1.32	0.298*	2.12	−1.267	−1.38	−10.89**	−2.27

an alternative measure, the total pounds of herbicides applied per acre in a given year. Both measures are practically proportional when considering a single herbicide active ingredient.[11] However, when dealing with a pesticide family we prefer to use the average number of herbicide applications per year because adding pounds of different active ingredients is questionable (Fernandez-Cornejo and Jans) since it implicitly assumes that a pound of any two ingredients has the same potency and other characteristics.[12] The definition and means of the main variables are presented in Table 1.

Because of the complexity of the survey design (the sample is not a simple random sample), a weighted least squares (WLS) technique is used to estimate the parameters using full-sample weights developed by the National Agricultural Statistics Service (NASS) of the USDA. A delete-a-group jackknife method is used to calculate the variances and standard errors because of the survey design and also because the conventional variance formulas do not apply to this type of model (Lee, Maddala, and Trost). The method follows the logic of

[11] For a single active ingredient, pounds per acre per year are equal to the number of applications times the application rate. There is less variability in the application rates because those rates "are recommended by the manufacturer of the product" and those recommendations "are generally followed." (USDA, 1998).

[12] Typically, each pesticide active ingredient has a different potency, and, consequently, is applied at a different recommended rate to provide a given level of pest control. A pesticide application, on the other hand, is designed to provide a certain level of pest control for a given target pest, and, thus, each application approximately provides a similar level or degree of control. Farmers will often adjust the number of applications to maintain the pest population below a threshold level.

the standard jackknife method except that a group of observations is deleted in each replication. It consists of partitioning the sample data into r groups of observations (r = 15 in this survey) and resampling, thus forming 15 replicates and deleting one group of observations in each replicate (Rust; Kott; Kott and Stukel). A set of sampling weights is calculated by NASS for each replicate. The model is run first with the full-sample weights to obtain the parameter estimates ***b***. The model is then run 15 additional times (using each of the 15 replicate weights) and the vector of parameters obtained in each case ***b(k)*** is compared to the full-sample parameter vector ***b*** in order to calculate the standard errors $se(\boldsymbol{b})$:

$$se(\boldsymbol{b}) = \sqrt{\left[c \cdot \sum_{k} [\boldsymbol{b}(k) - \boldsymbol{b}][\boldsymbol{b}(k) - \boldsymbol{b}]'\right]},$$

where $k = 1, 2, \ldots 15$ and

$c = 14/15$

Results

Soybean production in the U.S. uses a large amount of herbicides, and 97 percent of the 66.2 million acres devoted to soybean production in the 19 major states were treated with more than 78 million pounds of herbicides in 1997 (USDA, 1998). As Table 2 shows, pendimethalin was the top herbicide, as farmers applied more than 17 million pounds of this chemical in 1997. Glyphosate was second (15 million pounds), followed by trifluralin (12 million pounds) and metolachlor (9 million pounds).

Table 3 presents results from the probit regressions of the adoption of herbicide-tolerant soybeans and other weed-management practices. Among the statistically significant variables in the adoption of herbicide-tolerant soybeans, the size and education coefficients are positive, corroborating other findings (Feder, Just, and Zilberman) that larger operations and more educated operators are more likely to adopt agricultural innovations. Crop price is significant and positive, as expected, because more profitable operations are more likely to adopt agricultural innovations.[13] Another significant factor is the use of conventional tillage. This factor has a negative association with adoption as expected, since farmers using conventional tillage have less of a need to use herbicides compared to operators using conservation or no-till practices. Other significant factors include infestation levels and seed price. This last factor was positive, implying that users of herbicide-resistant soybeans buy more expensive seeds, even excluding technical fees. Factors not having a significant influence on adoption include the proxy for risk (debt-to-assets ratio) and the use of production/marketing contracts.

Tables 3 and 4 present the results of the adoption impacts model using the ITSUR estimation framework. The model has 45 estimated parameters and almost 40 percent of them are significant. Focusing first on the results for herbicide use, the use of "other herbicides" is negatively related to the adoption of herbicide-tolerant soybeans (significant at the 1-percent level). The elasticity of demand of other herbicides with respect to the probability of adoption of herbicide-resistant soybeans (calculated at the mean) is −0.13 (Table 5). That is, a 10-percent increase in the probability of adoption of herbicide-resistant soybeans would decrease the average number of applications of other herbicides by 1.3 percent.[14] This is an important result given that

[13] Adoption is expected to increase with expected crop prices because yield gains due to the new technology become more valuable with higher prices and allow farmers to afford to pay higher seed prices (technical fees) up-front, to be recovered later with profits arising form higher revenues (due to the higher yields) and/or lower herbicide costs. Similar price effects have been found for the adoption of other agricultural innovations, as higher expected margins allow farmers to invest more in information search efforts about the new technology (Feder, Just, and Zilberman).

[14] Results are typically expressed as a unitless measure, an elasticity—the percent change in a particular effect (herbicide use, yields, or profits) relative to a small percent change in adoption of the technology from current levels. The results can be viewed in terms of the aggregate effect (across an entire agricultural region or sector) from aggregate increases in adoption (as more and more producers adopt the technology). However, in terms of a typical farm—that has either

Table 4. ITSUR Parameter Estimates of the Profit Function U.S. Soybean Producers, 1997

Variable	Parameter Estimates	Standard Errors	t-Statistic
A0	−9.1236	9.8966	−0.9219
Ay	31.5817	9.6453	3.2743
A1	−0.0608	0.1149	−0.5290
A2	0.7130	0.9818	0.7262
A3	−0.2130	0.2031	−1.0488
C1	−1.2957	1.2507	−1.0360
C2	1.3987	0.7109	1.9675
C3	−7.9954	2.8963	−2.7605
C4	−16.4286	3.8537	−4.2631
C5	17.3386	13.7672	1.2594
C6	−1.8922	7.0305	−0.2691
Gyy	0.6836	3.6316	2.6665
Gy1	−0.0335	0.0294	−1.1380
Gy2	0.7363	0.1029	7.1534
Gy3	−0.0129	0.0387	−0.3324
G11	0.6996	0.0315	22.2034
G12	−0.0030	0.0028	−1.0887
G13	0.0008	0.0073	0.1112
G22	0.0150	0.0508	0.2955
G23	−0.0054	0.0039	−1.4095
G33	0.3731	0.0111	33.7019
Fy1	−2.4528	0.8428	−2.9103
Fy2	0.3743	0.6723	0.5568
Fy3	−4.9704	1.3139	−3.7830
Fy4	6.9183	3.0660	2.2564
Fy5	0.6768	5.1616	0.1311
Fy6	−10.8908	4.8016	−2.2682
E11	−0.0035	0.0150	−0.2310
E12	−0.0008	0.0117	−0.0673
E13	−0.0312	0.0218	−1.4325
E21	−0.2813	0.1135	−2.4790
E22	0.1844	0.0866	2.1300
E23	−0.2635	0.3554	−0.7413
E31	0.0134	0.0162	0.8253
E32	−0.0324	0.0201	−1.6132
E33	0.0167	0.0597	0.2792
E14	−0.0511	0.0524	−0.9734
E15	0.2640	0.2079	1.2699
E16	−0.1840	0.1396	−1.3181
E24	−1.6442	0.4961	−3.3141
E25	1.6540	1.3842	1.1949
E26	−1.2625	0.9155	−1.3790
E34	0.4803	0.1372	3.5018
E35	0.1209	0.2616	0.4620
E36	0.2980	0.1404	2.1224

Table 5. The Impact of Adoption of Herbicide-Tolerant Soybeans, 1997

Elasticity of	Elasticity with Respect to Probability of Adoption
Yields	+0.03
Variable Profits	0[1]
Herbicide use	
Acetamide herbicides	0[1]
Other synthetic herbicides	−0.13
Glyphosate	+0.37

[1] Insignificant underlying coefficients.

"other herbicides" constitutes by far the most important herbicide "family" in terms of total amount used annually. Use of other herbicides amounted to nearly 50 million pounds out a total of 78 million pounds for all herbicides in 1997 (Table 2).

On the other hand, use of glyphosate is positively related to the adoption of herbicide-resistant soybeans (also significant at the 1-percent level), which is expected given that glyphosate is the herbicide that most herbicide-tolerant soybeans have been engineered to resist. The elasticity of demand of glyphosate with respect to the probability of adoption of herbicide resistant soybeans is 0.37. While the elasticity for glyphosate is comparatively high, the increase in the amount of glyphosate is not very large because of the relatively small base amount. As expected, the use of acetamide herbicides is also negatively related to the probability of adoption of herbicide resistant soybean, but the corresponding coefficient is not significant.

Table 3 also shows that the effect of adoption of herbicide-resistant soybeans on yields is positive and significant at the 5-percent level, but small. The elasticity of yields with respect to the probability of adoption of herbicide-resistant soybeans is 0.03 (Table 5).

adopted or not—the elasticity is usually interpreted as the (marginal) farm-level effect associated with an increase in the probability of adoption. Moreover, as with most cases in economics, elasticities examine small changes (say, less than 10 percent) away from a given, e.g., current level of adoption.

Finally, the effect of adoption of herbicide-tolerant soybeans on variable profits is calculated by taking the derivative of equation 1 with respect to the probability of adoption ($\partial\tilde{\pi}/\partial R_A$) using the ITSUR parameter estimates of the profit function (Table 4). The adoption of herbicide-resistant soybeans does not have a statistically significant effect on variable profits.

For comparison, and to examine the robustness of the results, we also estimated the model using pounds/acre-year as an alternative measure of herbicide use. The results are similar: the elasticity of yields is about the same (+0.03) and the elasticity of profits continues to be insignificant. The elasticity of herbicide use for the acetamide family remains insignificant; for glyphosate (+0.19) it is significant but smaller than the elasticity obtained using the average number of herbicide applications per year as a measure of herbicide use, and the elasticity for other herbicides is also smaller in absolute value (−0.09). Using these elasticities at the mean, we also estimate the substitution of glyphosate for other herbicides. Since the total amount of glyphosate used in soybeans in 1997 was 14.9 million pounds (Table 2), much lower than that of other herbicides (49.9 million pounds, Table 2), we estimate that the annual reduction in other herbicides associated with a 10-percent increase in adoption is 0.45 million pounds, slightly greater than the increase in glyphosate (0.3 million pounds) that replaces them.

Concluding Comments

This paper estimates the on-farm impacts of adopting herbicide-tolerant soybean on herbicide use, yields, and farm profits using an econometric model that corrects for self-selection and simultaneity and is consistent with profit maximization. The model is estimated using 1997 national survey data.

Herbicide use (except for glyphosate) is negatively related to the adoption of herbicide-tolerant varieties in soybean production. These results confirm anecdotal evidence that a large number of soybean farmers are substituting glyphosate for other herbicides and that the total amount of herbicides used on soybeans is being reduced slightly.

The environmental and health implications of this substitution are not entirely clear, as active ingredients vary widely in toxicity and in their persistence in the environment. However, the possible health/enviromental effects of changes in herbicide use associated with the adoption of herbicide-tolerant soybeans (substitution of glyphosate for other herbicides, such as imazethapyr, bentazon, metribuzin, pendimethalin, Table 2) may be explored observing that glyphosate has a half-life in the environment of 47 days, compared with 60–90 days for the herbicides it replaces (Heimlich et al.). Moreover, using a chronic risk indicator based on the EPA reference dose for humans (USDA, 1997, pp. 122–25), the herbicides that glyphosate replaces are 3.4 to 16.8 times more toxic than glyphosate (Heimlich et al.). Thus the substitution enabled by herbicide-tolerant soybeans results in glyphosate replacing other synthetic herbicides, which are at least three times more toxic and persist in the environment nearly twice as long.

The market ramifications of increased glyphosate use are already being felt by competing chemical producers. Glyphosate's market share of the soybean herbicide market has expanded and glyphosate prices as well as prices of other herbicide competitors have fallen substantially (Hayenga). Glyphosate prices are expected to fall further because its patent (Roundup) expired in 2000.

Our results show that there was a small yield advantage associated with farmers adopting herbicide-tolerant soybeans, but, on average, profits are not (statistically) significantly affected by adoption. Unlike the findings of economic analyses based on experimental data, which have mostly shown that the economics of herbicide-tolerant crops compare favorably to conventional varieties, our results are more in line with analyses based on farm surveys, which have not been as definitive.

Perhaps the biggest challenge raised by these results is how to explain the rapid adoption of herbicide-tolerant soybeans even though positive financial impacts could not be demonstrated. Why would farmers still choose to adopt herbicide-tolerant soybean if profits are not higher than under traditional herbicide systems? Other research has suggested that the increased planting flexibility and simplicity of the herbicide-tolerant program (not completely captured by our model because of measurement difficulties) have been the primary reasons that growers are adopting (Carpenter and Gianessi). Also, growers may have initially responded to the potential savings from herbicide-tolerant soybeans that have since been diminished by price cuts on conventional herbicides.

The economic potential of herbicide-tolerant crops is difficult to assess. Returns from herbicide-tolerant soybeans are realized only if the weed infestation levels and prices are such that the gains from increased yields and/or reduced herbicide costs exceeds the premium paid for the seed. This requires farmers to forecast input and output prices and infestation levels because the adoption decision must be made before planting. Since conditions across the U.S. are far from homogeneous, it is likely that herbicide tolerant-soybeans may have been used on some acreage where the value of increase yields and/or reduced herbicide costs was lower than the seed premium. Possible reasons for this "over-adoption" are annual variations in weather and poor forecasts of input and output prices and yield losses due to infestations.

The implications of these results should be regarded carefully and only within the constraints of the analysis. As mentioned before, the economic impacts of adopting GE crops may vary with several factors, most notably pest infestations, seed premiums, prices of alternative pest-control programs, and any premiums paid for segregated crops. These factors have changed, and will likely continue to change over time as technology, marketing strategies for GE and conventional crops, and consumer perceptions of GE crops continue to evolve. Finally, this study has two limitations. The modeling of the substitution possibilities between pesticides and other purchased inputs, particularly fertilizers, is incomplete and production risk was excluded from the model. In the first case, the limitations are attributable to the lack of farm-level price input data for some inputs. Panel data would be needed to address the second issue satisfactorily. When better data become available, these limitations will be surmounted, helping to improve our understanding of technology adoption in agriculture.

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